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Putra, S.S.S.[a] , Chew, C.Y.[a] , Hayyan, A.[a b] , Elgharbawy, A.A.M.[c d] , Taskin-Tok, T.[e f] , Hayyan, M.[g] , Ngoh, G.C.[a] , Saleh, J.[h] , Al Abdulmonem, W.[i] , Alghsham, R.S.[i] , Nor, M.R.M.[j] , Aldaihani, A.G.H.[k] , Basirun, W.J.[l]

Nanodiamonds and natural deep eutectic solvents as potential carriers for lipase

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[a] Department of Chemical Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur, 50603, Malaysia
[b] Sustainable Process Engineering Centre (SPEC), Faculty of Engineering, Universiti Malaya, Kuala Lumpur, 50603, Malaysia
[c] International Institute for Halal Research and Training (INHART), International Islamic University Malaysia, Kuala Lumpur, 50728, Malaysia
[d] Bioenvironmental Engineering Research Centre (BERC), Department of Biotechnology Engineering, Faculty of Engineering, International Islamic University Malaysia (IIUM), Kuala Lumpur, 53100, Malaysia
[e] Gaziantep University, Faculty of Arts and Sciences, Department of Chemistry, Gaziantep, Turkey
[f] Gaziantep University, Institute of Health Sciences, Department of Bioinformatics and Computational Biology, Gaziantep, Turkey
[g] Chemical Engineering Program, Faculty of Engineering & Technology, Muscat University, PO Box 550, Muscat, P.C.130, Oman
[h] Chemical Engineering Department, King Saud University, P.O. Box 800, Riyadh, 11421, Saudi Arabia
[i] Department of Pathology, College of Medicine, Qassim University, Buraydah, 51452, Saudi Arabia
[j] Halal Research Group, Academy of Islamic Studies, Universiti Malaya, Kuala Lumpur, 50603, Malaysia
[k] School of Engineering, University of Liverpool, Liverpool, L69 3GH, United Kingdom
[l] Department of Chemistry, Faculty of Science, Universiti Malaya, Kuala Lumpur, 50603, Malaysia

Abstract
This study investigates the use of nanodiamonds (ND) as a promising carrier for enzyme immobilization and compares the effectiveness of immobilized and native enzymes. Three different enzyme types were tested, of which Rhizopus niveus lipase (RNL) exhibited the highest relative activity, up to 350 %. Under optimized conditions (1 h, pH 7.0, 40 °C), the immobilized ND-RNL showed a maximum specific activity of 0.765 U mg−1, significantly higher than native RNL (0.505 U mg−1). This study highlights a notable enhancement in immobilized lipase; furthermore, the enzyme can be recycled in the presence of a natural deep eutectic solvent (NADES), retaining 76 % of its initial activity. This aids in preserving the native conformation of the protein throughout the reusability process. A test on brine shrimp revealed that even at low concentrations, ND-RNL had minimal toxicity, indicating its low cytotoxicity. The in silico molecular dynamics simulations performed in this study offer valuable insights into the mechanism of interactions between RNL and ND, demonstrating that RNL immobilization onto NDs enhances its efficiency and stability. All told, these findings highlight the immense potential of ND-immobilized RNL as an excellent candidate for biological applications and showcase the promise of further research in this field. © 2024 Elsevier B.V.

Author Keywords
Molecular dynamics; Natural deep eutectic solvents; Rhizopus niveus lipase

Index Keywords
Enzyme immobilization, Eutectics, Nanodiamonds, Reusability, Solvents; Deep eutectic solvents, Immobilized enzyme, Immobilized lipase, Initial activity, Native enzymes, Natural deep eutectic solvent, Optimized conditions, Relative activities, Rhizopus niveu lipase, Specific activity; Molecular dynamics; nanodiamond, natural deep eutectic solvent, solvent, triacylglycerol lipase, unclassified drug; Artemia, Article, binding affinity, catalytic efficiency, colorimetry, controlled study, cytotoxicity, enzymatic assay, enzyme activity, enzyme immobilization, half life time, LC50, Michaelis constant, molecular dynamics, nonhuman, pH, pig, Rhizopus, Rhizopus niveus, turnover number

Chemicals/CAS
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References

- Magadum, D.B., Yadav, G.D.
  Enantioselective resolution of (R,S)-A-methyl-4-pyridinemethanol using immobilized biocatalyst: optimization and kinetic modeling
  (2017) *Biochem. Eng. J.*, 122, pp. 152-158.

- Kralovec, J.A., Wang, W., Barrow, C.J.
Production of omega-3 triacylglycerol concentrates using a new food grade immobilized Candida antarctica lipase B
(2010) *Aust. J. Chem.*, 63, pp. 922-928.

- Wang, Y., Zhang, Y., Jiang, T., Meng, J., Sheng, B., Yang, C., Gao, C., Ma, C.
A novel biocatalyst for efficient production of 2-oxo-carboxylates using glycerol as the cost-effective carbon source
(2015) *Biotechnol. Biofuels*, 8, pp. 1-11.

- Spahn, C., Minteer, S.
Enzyme immobilization in biotechnology
(2008) *Recent Patents Eng.*, 2, pp. 195-200.

- Khan, A.K., Mubarak, N.M., Abdullah, E.C., Khalid, M., Nizamuddin, S., Baloch, H.A., Siddiqui, M.T.H.
Immobilization of lipase enzyme carbon nanotubes via adsorption
(2019) *IOP Conf. Ser. Mater. Sci. Eng.*, 495.

- Du, Y., Gao, J., Zhou, L., Ma, L., He, Y., Huang, Z., Jiang, Y.
Enzyme nanocapsules armored by metal-organic frameworks: a novel approach for preparing nanobiocatalyst
(2017) *Chem. Eng. J.*, 327, pp. 1192-1197.

- Tavares, A.P.M., Silva, C.G., Dražić, G., Silva, A.M.T., Loureiro, J.M., Faria, J.L.
Laccase immobilization over multi-walled carbon nanotubes: kinetic, thermodynamic and stability studies
(2015) *J. Colloid Interface Sci.*, 454, pp. 52-60.

- Liu, D.M., Chen, J., Shi, Y.P.
Tyrosinase immobilization on aminated magnetic nanoparticles by physical adsorption combined with covalent crosslinking with improved catalytic activity, reusability and storage stability
(2018) *Anal. Chim. Acta*, 1006, pp. 90-98.

- Abd El Aty, A.A., Mostafa, F.A., Hassan, M.E., Hamed, E.R., Esawy, M.A.
Covalent immobilization of Alternaria tenuissima KM651985 laccase and some applied aspects
(2017) *Biocatal. Agric. Biotechnol.*, 9, pp. 74-81.

- Liu, D.M., Dong, C.
Recent advances in nano-carrier immobilized enzymes and their applications
(2020) *Process Biochem.*, 92, pp. 464-475.

- Rastian, Z., Khodadadi, A.A., Guo, Z., Vahabzadeh, F., Mortazavi, Y.
Plasma functionalized multiwalled carbon nanotubes for immobilization of candida antarctica lipase B: production of biodiesel from methanolysis of rapeseed oil
(2016) *Appl. Biochem. Biotechnol.*, 178, pp. 974-989.

- Wan, X., Tang, S., Xiang, X., Huang, H., Hu, Y.
Immobilization of Candida antarctic lipase B on functionalized ionic liquid modified MWNTs
(2017) *Appl. Biochem. Biotechnol.*, 183, pp. 807-819.

- Junqueira, M., Brito, P., Pereira, M., Santos, F., Cardozo, E., Júnior, D.S., Soares, L., Martins, C.
Development of activated carbon from pupunha palm heart sheaths: effect of synthesis conditions and its application in lipase immobilization
(2020) *J. Environ. Chem. Eng.*, 8.

- Mochalin, V.N., Shenderova, O., Ho, D., Gogotsi, Y.
The properties and applications of nanodiamonds
(2012) *Nat. Nanotechnol.*, 7, pp. 11-23.

- Zhang, X., Hu, W., Li, J., Tao, L., Wei, Y.
A comparative study of cellular uptake and cytotoxicity of multi-walled carbon nanotubes, graphene oxide, and nanodiamond
(2012) *Toxicol. Res. (Camb).*, 1, pp. 62-68.

- Mumtaz, M., Hussain, N., Salam, S., Bilal, M.
Multifunctional nanodiamonds as emerging platformsfor cancer treatment, and targeted delivery of geneticfactors and protein medications—a review
(2022) *J. Mater. Sci.*, 57, pp. 8064-8099.

- El Tall, O., Hou, Y., Abou-Hamad, E., Raja, I.U., Hedhili, M.N., Peng, W., Mahfouz, R., Beaujuge, P.M.
Direct functionalization of nanodiamonds with maleimide
(2014) *Chem. Mater.*, 26, pp. 2766-2769.

- Wei, L., Zhang, W., Lu, H., Yang, P.
Immobilization of enzyme on detonation nanodiamond for highly efficient proteolysis
(2010) *Talanta*, 80, pp. 1298-1304.

- Ansari, S.A., Satar, R., Zaidi, S.K., Naseer, M.I., Karim, S., Alqahtani, M.H., Rasool, M.
Nanodiamonds as an effective and novel matrix for immobilizing β galactosidase
(2015) *Food Bioprod. Process.*, 95, pp. 298-303.

- Ghalkhani, M., Teymourinia, H., Ebrahimi, F., Irannejad, N., Karimi-Maleh, H., Karaman, C., Karimi, F., Singh, J.
Engineering and application of polysaccharides and proteins-based nanobiocatalysts in the recovery of toxic metals, phosphorous, and ammonia from wastewater: a review
(2023) *Int. J. Biol. Macromol.*, 242.

- Putra, S.S.S., Basirun, W.J., Elgharbawy, A.A.M., Hayyan, A., Hayyan, M., Mohammed, M.A.
Nanocellulose and natural deep eutectic solvent as potential biocatalyst system toward enzyme immobilization
(2022) *Mol. Catal.*, 528, pp. 1-37.

- Malek, A., A., S., Li, K., Wang, J., Ghide, M.K., Yan, Y.
Enhanced performance of Rhizopus oryzae lipase immobilized onto a hybrid-nanocomposite matrix and its application for biodiesel production under the assistance of ultrasonic technique
(2022) *Fuel Process. Technol.*, 232.

- Qiao, Q., Shi, J., Shao, Q.
Effect of water on solvation and structure of lipase in deep eutectic solvents containing protein destabilizer and stabilizer
(2021) *Phys. Chem. Chem. Phys.*,

- Petit, T., Puskar, L., Dolenko, T., Choudhury, S., Ritter, E., Burikov, S., Laptinskiy, K., Aziz, E.F.
Unusual water hydrogen bond network around hydrogenated nanodiamonds
(2017) *J. Phys. Chem. C*, 121, pp. 5185-5194.

- Tjørnelund, H.D., Vind, J., Brask, J., Woodley, J.M., Peters, G.H.J.
Candida antarctica lipase B performance in organic solvent at varying water activities studied by molecular dynamics simulations
(2023) *Comput. Struct. Biotechnol. J.*, 21, pp. 5451-5462.

- Wang, Z., Wen, J., Zhang, J., Deng, J., Zhuang, W., Liu, J., Wang, Z., Ying, H.
Atomic insights into the mechanism of trace water influence on lipase catalysis in organic media
(2023) *Chem. Eng. J.*, 464.

- Dassault Systèmes BIOVIA
Discovery Studio Modelling Environment
(2019), Dassault Systèmes San Diego

- Phillips, J.C., Braun, R., Wang, W., Gumbart, J., Tajkhorshid, E., Villa, E., Chipot, C., Schulten, K.
Scalable molecular dynamics with NAMD
(2005) *J. Comput. Chem.*, 26, pp. 1781-1802.

- Lee, J., Cheng, X., Jo, S., MacKerell, A.D., Klauda, J.B., Im, W.
CHARMM-GUI input generator for NAMD, Gromacs, Amber, Openmm, and CHARMM/OpenMM simulations using the CHARMM36 additive force field
(2016) *Biophys. J.*, 110, p. 641a.

- Bayel Secinti, B., Tatar, G., Taskin Tok, T.
Determination of potential selective inhibitors for ROCKI and ROCKII isoforms with molecular modeling techniques: structure based docking, ADMET and molecular dynamics simulation
(2019) *J. Biomol. Struct. Dyn.*, 37, pp. 2457-2463.

- Kumar, R., Jade, D., Gupta, D.
A novel identification approach for discovery of 5-HydroxyTriptamine 2A antagonists: combination of 2D/3D similarity screening, molecular docking and molecular dynamics
(2019) *J. Biomol. Struct. Dyn.*, 37, pp. 931-943.

- Sixto-López, Y., Bello, M., Correa-Basurto, J.
Insights into structural features of HDAC1 and its selectivity inhibition elucidated by molecular dynamic simulation and molecular docking
(2019) *J. Biomol. Struct. Dyn.*, 37, pp. 584-610.

- Facin, B.R., Melchiors, M.S., Valério, A., Oliveira, J.V., De Oliveira, D.
Driving immobilized lipases as biocatalysts: 10 years state of the art and future prospects
(2019) *Ind. Eng. Chem. Res.*, 58, pp. 5358-5378.

- Maghraby, Y.R., El-shabasy, R.M., Ibrahim, A.H., Azzazy, H.M.E.
Enzyme immobilization technologies and industrial applications
(2023) *ACS Pub.*, 8, pp. 5184-5196.

- Remonatto, D., Miotti, R.H., Monti, R., Bassan, J.C., de Paula, A.V.
Applications of immobilized lipases in enzymatic reactors: a review
(2022) *Process Biochem.*, 114, pp. 1-20.

- Sánchez, D.A., Tonetto, G.M., Ferreira, M.L.
Burkholderia cepacialipase: a versatile catalyst in synthesis reactions
(2017) *Biotechnol. Bioeng.*, 115, pp. 6-24.

- Rabbani, G., Ahmad, E., Ahmad, A., Khan, R.H.
Structural features, temperature adaptation and industrial applications of microbial lipases from psychrophilic, mesophilic and thermophilic origins
(2023) *Int. J. Biol. Macromol.*, 225, pp. 822-839.

- López-Fernández, J., Benaiges, M.D., Valero, F.
Constitutive expression in komagataella phaffii of mature Rhizopus oryzae lipase

jointly with its truncated prosequence improves production and the biocatalyst operational stability
(2021) *Catalysts*, 11.

- Ghamgui, H., Miled, N., Karra-chaâbouni, M., Gargouri, Y.
Immobilization studies and biochemical properties of free and immobilized Rhizopus oryzae lipase onto CaCO₃: a comparative study
(2007) *Biochem. Eng. J.*, 37, pp. 34-41.

- Gupta, M.N., Kaloti, M., Kapoor, M., Solanki, K.
Nanomaterials as matrices for enzyme immobilization
(2011) *Artif. Cells, Blood Substitutes, Biotechnol.*, 39, pp. 98-109.

- Khosravi, H., Sajedi Hosseini, F., Nasrollahi, M.
Trend analysis and detection of precipitation fluctuations in arid and semi-arid regions
(2017) *Desert*, 22, pp. 77-84.

- Guo, L.P., Yu, Q., Gao, P., Nie, X.F., Liao, K.T., Chen, X.L., Hu, J.M., Mu, X.M.
Trend and change-point analysis of streamflow and sediment discharge of the Gongshui River in China during the last 60 years
(2018) *Water (Switzerland).*, 10.

- Guimar, R., Rocha-martin, J., Tardioli, P.W., Gonçalves, L.R.B., Fernandez-lafuente, R.
(2022) *Determination of immobilized lipase stability depends on the substrate and activity determination condition: stress inactivations and optimal temperature as biocatalysts stability indicators*, 29.

- Helal, S.E., Abdelhady, H.M., Abou-Taleb, K.A., Hassan, M.G., Amer, M.M.
Lipase from Rhizopus oryzae R1: in-depth characterization, immobilization, and evaluation in biodiesel production
(2021) *J. Genet. Eng. Biotechnol.*, 19, pp. 1-13.

- Pashangeh, K., Akhond, M., Karbalaei-Heidari, H.R., Absalan, G.
Biochemical characterization and stability assessment of Rhizopus oryzae lipase covalently immobilized on amino-functionalized magnetic nanoparticles
(2017) *Int. J. Biol. Macromol.*, 105, pp. 300-307.

- Yu, D., Li, Z., Zhou, X., Wang, W., Wang, L., Liu, T., Du, J.
Study on the modification of magnetic graphene oxide and the effect of immobilized lipase
(2022) *Int. J. Biol. Macromol.*, 216, pp. 498-509.

- Sani, F., Mokhtar, N.F., Ali, M.S.M., Rahman, R.N.Z.R.A.
Enhanced performance of immobilized rhizopus oryzae lipase on coated porous polypropylene support with additives
(2021) *Catalysts*, 11, pp. 1-13.

- Del Monte, F., Carriazo, D., Serrano, M.C., Gutiérrez, M.C., Ferrer, M.L.
Deep eutectic solvents in polymerizations: a greener alternative to conventional syntheses
(2014) *ChemSusChem*, 7, pp. 999-1009.

- Atiroğlu, V.
Lipase immobilization on synthesized hyaluronic acid-coated magnetic nanoparticle-functionalized graphene oxide composites as new biocatalysts: improved reusability, stability, and activity
(2020) *Int. J. Biol. Macromol.*, 145, pp. 456-465.

- Bilal, M., Dourado, C., Mehmood, T., Nadeem, F., Tabassam, Q., Fernando, L., Ferreira, R.
Immobilized lipases-based nano-biocatalytic systems — a versatile platform with

incredible biotechnological potential
(2021) *Int. J. Biol. Macromol.*, 175, pp. 108-122.

- Sarno, M., Iuliano, M., Polichetti, M., Ciambelli, P.
High activity and selectivity immobilized lipase on Fe₃O₄ nanoparticles for banana flavour synthesis
(2017) *Process Biochem.*, 56, pp. 98-108.

- Awad, G.E.A., Ghanem, A.F., Abdel Wahab, W.A., Wahba, M.I.
Functionalized κ-carrageenan/hyperbranched poly(amidoamine)for protease immobilization: thermodynamics and stability studies
(2020) *Int. J. Biol. Macromol.*, 148, pp. 1140-1155.

- Cao, X., Xu, H., Li, F., Zou, Y., Ran, Y., Ma, X., Cao, Y., Cao, Y.
One-step direct transesterification of wet yeast for biodiesel production catalyzed by magnetic nanoparticle-immobilized lipase
(2021) *Renew. Energy*, 171, pp. 11-21.

- Yang, X., Chen, Y., Yao, S., Qian, J., Guo, H., Cai, X.
Preparation of immobilized lipase on magnetic nanoparticles dialdehyde starch
(2019) *Carbohydr. Polym.*, 218, pp. 324-332.

- Aghaei, H., Ghavi, M., Hashemkhani, G., Keshavarz, M.
Utilization of two modified layered doubled hydroxides as supports for immobilization of Candida rugosa lipase
(2020) *Int. J. Biol. Macromol.*, 162, pp. 74-83.

- Zhong, L., Feng, Y., Hu, H., Xu, J., Wang, Z., Du, Y., Cui, J., Jia, S.
Enhanced enzymatic performance of immobilized lipase on metal organic frameworks with superhydrophobic coating for biodiesel production
(2021) *J. Colloid Interface Sci.*, 602, pp. 426-436.

- Jo, S., Park, S., Oh, Y., Hong, J., Kim, H.J., Kim, K.J., Oh, K.K., Lee, S.H.
Development of cellulose hydrogel microspheres for lipase immobilization
(2019) *Biotechnol. Bioprocess Eng.*, 24, pp. 145-154.

- Chapman, J., Ismail, A.E., Dinu, C.Z.
Industrial applications of enzymes: recent advances, techniques, and outlooks
(2018) *Catalysts*, 8, pp. 20-29.

- Suo, H., Xu, L., Xu, C., Chen, H., Yu, D., Gao, Z., Huang, H., Hu, Y.
Enhancement of catalytic performance of porcine pancreatic lipase immobilized on functional ionic liquid modified Fe₃O₄-chitosan nanocomposites
(2018) *Int. J. Biol. Macromol.*, 119, pp. 624-632.

- Suo, H., Li, M., Liu, R., Xu, L.
Enhancing bio-catalytic performance of lipase immobilized on ionic liquids modified magnetic polydopamine
(2021) *Colloids Surf. B: Biointerfaces*, 206.

- Garmroodi, M., Mohammadi, M., Ramazani, A., Ashjari, M., Mohammadi, J., Sabour, B., Yousefi, M.
Covalent binding of hyper-activated Rhizomucor miehei lipase (RML) on hetero-functionalized siliceous supports
(2016) *Int. J. Biol. Macromol.*, 86, pp. 208-215.

- Kaja, B.S., Lumor, S., Besong, S., Taylor, B., Ozbay, G.
Investigating enzyme activity of immobilized Candida rugosa lipase
(2018) *J. Food Qual.*, 2018.

- Liu, Z., Yang, Y., Dong, W., Liu, Q., Wang, R., Pang, J., Xia, X., Liu, Y.
Investigation on the enzymatic profile of mulberry alkaloids by enzymatic study and molecular docking
(2019) *Molecules*, 24.

- Ferreira, M.M., Santiago, F.L.B., Silva, N.A.G.D., Luiz, J.H.H., Fernandéz-Lafuente, R., Mendes, A.A., Hirata, D.B.
Different strategies to immobilize lipase from Geotrichum candidum: kinetic and thermodynamic studies
(2018) *Process Biochem.*, 67, pp. 55-63.

- Roskoski, R.
Michaelis-Menten Kinetics
(2015), Elsevier Inc.

- Wang, K., Sun, S., Ma, B., Dong, F., Huo, T., Li, X., Zhao, Y., Huang, Y.
Construction and characterization of a nanostructured biocatalyst consisting of immobilized lipase on aminopropyl-functionalized montmorillonite
(2019) *Appl. Clay Sci.*, 183.

- Liu, Y., Friesen, J.B., McAlpine, J.B., Lankin, D.C., Chen, S.N., Pauli, G.F.
Natural deep eutectic solvents: properties, applications, and perspectives
(2018) *J. Nat. Prod.*, 81, pp. 679-690.

- Xu, K., Chen, X., Zheng, R., Zheng, Y.
Immobilization of multi-enzymes on support materials for efficient biocatalysis
(2020) *Front. Bioeng. Biotechnol.*, 8, pp. 1-17.

- Buzatu, A.R., Soler, M.A., Fortuna, S., Ozkilinc, O., Dreavă, D.M., Bîtcan, I., Badea, V., Boeriu, C.G.
Reactive natural deep eutectic solvents increase selectivity and efficiency of lipase catalyzed esterification of carbohydrate polyols
(2024) *Catal. Today*, 426.

- Yao, J., Li, C., Xiao, L., Wu, Y., Wu, Q., Cui, Z., Wang, B.
Influence of natural deep eutectic solvents on stability and structure of cellulase
(2022) *J. Mol. Liq.*, 346.

- Delorme, A.E., Andanson, J.M., Verney, V.
Improving laccase thermostability with aqueous natural deep eutectic solvents
(2020) *Int. J. Biol. Macromol.*, 163, pp. 919-926.

- Taklimi, S.M., Divsalar, A., Ghalandari, B., Ding, X., Di Gioia, M.L., Omar, K.A., Saboury, A.A.
Effects of deep eutectic solvents on the activity and stability of enzymes
(2023) *J. Mol. Liq.*, 377.

- Kumar, S., Nehra, M., Kedia, D., Dilbaghi, N., Tankeshwar, K., Kim, K.H.
Nanodiamonds: emerging face of future nanotechnology
(2019) *Carbon N. Y.*, 143, pp. 678-699.

- Cui, J., Jia, S.
Organic–inorganic hybrid nanoflowers: a novel host platform for immobilizing biomolecules
(2017) *Coord. Chem. Rev.*, 352, pp. 249-263.

- Elgharbawy, A.A., Hayyan, A., Hayyan, M., Rashid, S.N., Nor, M.R.M., Zulkifli, M.Y., Alias, Y., Mirghani, M.E.S.
Shedding light on lipase stability in natural deep eutectic solvents
(2018) *Chem. Biochem. Eng. Q.*, 32, pp. 359-370.

- Li, S., Zhao, S., Hou, Y., Chen, G., Chen, Y., Zhang, Z.
Polylactic acid (PLA) modified by polyethylene glycol (PEG) for the immobilization of lipase
(2020) *Appl. Biochem. Biotechnol.*, 190, pp. 982-996.

- Abdulla, R., Sanny, S.A., Derman, E.
Stability studies of immobilized lipase on rice husk and eggshell membrane
(2017) *IOP Conf. Ser. Mater. Sci. Eng.*, 206, pp. 0-7.

- Mensink, M.A., Frijlink, H.W., van der Voort Maarschalk, K., Hinrichs, W.L.J.
How sugars protect proteins in the solid state and during drying (review): mechanisms of stabilization in relation to stress conditions
(2017) *Eur. J. Pharm. Biopharm.*, 114, pp. 288-295.

- Zhang, J., Gao, B., Lv, K., Kumissay, L., Wu, B., Chu, J., He, B.
Specific immobilization of lipase on functionalized 3D printing scaffolds via enhanced hydrophobic interaction for efficient resolution of racemic 1-indanol
(2021) *Biochem. Biophys. Res. Commun.*, 546, pp. 111-117.

- Rehman, S., Wang, P., Bhatti, H.N., Bilal, M., Asgher, M.
Improved catalytic properties of Penicillium notatum lipase immobilized in nanoscale silicone polymeric films
(2017) *Int. J. Biol. Macromol.*, 97, pp. 279-286.

- Ren, W., Li, Y., Wang, J., Li, L., Xu, L., Wu, Y., Wang, Y., Tian, J.
Synthesis of magnetic nanoflower immobilized lipase and its continuous catalytic application
(2019) *New J. Chem.*, 43, pp. 11082-11090.

- Ma, Q., Zhang, Q., Yang, S., Yilihamu, A., Shi, M., Ouyang, B., Guan, X., Yang, S.T.
Toxicity of nanodiamonds to white rot fungi Phanerochaete chrysosporium through oxidative stress
(2020) *Colloids Surf. B: Biointerfaces*, 187.

- Lee, D.K., Ha, S., Jeon, S., Jeong, J., Kim, D.J., Lee, S.W., Cho, W.S.
The sp³/sp² carbon ratio as a modulator of in vivo and in vitro toxicity of the chemically purified detonation-synthesized nanodiamond via the reactive oxygen species generation
(2020) *Nanotoxicology*, 14, pp. 1213-1226.

- Zhang, Y., Zhang, W., Fedutik, Y., Mao, Z., Gao, C.
Nanodiamonds of different surface chemistry influence the toxicity and differentiation of rat bone mesenchymal stem cells in vitro
(2019) *J. Nanosci. Nanotechnol.*, 19, pp. 5426-5434.

- Tseng, P.H., Sie, Z.L., Liu, M.C., Lin, H.S., Yang, W.Y., Lin, T.Y., Hsieh, H.P., Yuh, C.H.
Identification of two novel small compounds that inhibit liver cancer formation in zebrafish and analysis of their conjugation to nanodiamonds to further reduce toxicity
(2019) *Adv. Ther.*, 2, pp. 1-14.

- Keselowsky, B.G., Collard, D.M., García, A.J.
Surface chemistry modulates integrin binding to direct cell adhesion and function
(2003) *J. Biomed. Mater. Res. Part A.*, p. 369.

- Su, L., Krim, J., Brenner, D.W.
Interdependent roles of electrostatics and surface functionalization on the adhesion strengths of nanodiamonds to gold in aqueous environments revealed by molecular dynamics simulations
(2018) *J. Phys. Chem. Lett.*, 9, pp. 4396-4400.

Correspondence Address

Hayyan A.; Department of Chemical Engineering, Malaysia; email: adeeb.hayyan@yahoo.com
Elgharbawy A.A.M.; International Institute for Halal Research and Training (INHART), Malaysia; email: amalgh@iium.edu.my
Hayyan M.; Chemical Engineering Program, PO Box 550, Oman; email: maan_hayyan@yahoo.com

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